Chlorine Disinfection in the Use of Individual Water Purification Devices

Technical Information Paper #31-002-0306

PURPOSE

This information paper provides an in-depth review of chlorine as a disinfectant in potable water supplies. This paper is intended to assist the reader in evaluating the disinfection capabilities of Individual Water Purification Devices (IWPDs) using chlorine to kill or inactivate disease-causing bacteria, viruses, and protozoan cysts.

REFERENCES

Appendix A contains a list of references.

INTRODUCTION

Background

Understanding the disinfection capabilities of chlorine to kill or inactivate disease-causing microorganisms is important in protecting Soldiers, who are considering using this technology, from acute health threats posed by these microorganisms. Soldiers deployed beyond traditional field drinking water supplies must have access to potable water. Using IWPDs is one way to provide potable water in these situations. These IWPDs must protect the Soldier from acute microbial health threats. The U.S. Environmental Protection Agency (USEPA) Guide Standard and Protocol for Testing Microbiological Water Purifiers (reference 1) provides performance standards by which an IWPD using chlorine can be evaluated. The performance standards are a minimum 6-log reduction/inactivation of bacteria, 4-log reduction/inactivation of viruses, and 3-log reduction/inactivation of protozoan cysts. Chlorine-using IWPDs meeting these standards are considered effective against disease causing bacteria, viruses, and protozoan cysts. Some IWPD manufacturers test their devices using this protocol. This is the best way to evaluate the IWPDs disinfection capabilities. In the absence of that testing data, this information paper can be used to gain an understanding of chlorine disinfection capabilities and help determine if an IWPD using chlorine could successfully meet the EPA Guide's minimum performance standards.

General

Chlorine has long been identified as an effective and efficient disinfection agent. One-time, emergency chlorination of water supplies has been practiced for over 100 years, with the first continuous use of chlorine for water supply disinfection occurring in Boonton, New Jersey, in 1908 (references 2 and 3). Chlorine and its derivatives represent the most widespread compound

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14. ABSTRACT

Soldiers deployed beyond traditional field drinking water supplies must have access to potable water. Using Individual Water Purification Devices (IWPDs) is one way to provide potable water in these situations. Such IWPDs must protect the Soldier from acute microbial health threats. Understanding the disinfection capabilities of chlorine to kill or inactivate disease-causing microorganisms is important in protecting Soldiers, who are considering using this technology, from acute health threats posed by these microorganisms. This information paper provides an in-depth review of chlorine as a disinfectant in potable water supplies. This paper is intended to assist the reader in evaluating the disinfection capabilities of IWPDs using chlorine to kill or inactivate disease-causing bacteria, viruses, and protozoan cysts.

15. SUBJECT TERMS

water; drinking water; water treatment; purification; disinfection; chlorine; chlorine disinfection; military; IWP (individual water purifier); pathogen removal

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used for disinfection in the United States. There are several Commercial-Off-The-Shelf (COTS) IWPDs that use chlorine for disinfection, including Chlor-Floc™, which was tested by an Army agency and found to be a safe alternative to iodine tablets (reference 4). These IWPDs may either rely on chlorine disinfection alone or combine chlorine disinfection with filtration to remove pathogenic organisms from water.

CHLORINE CHEMISTRY IN WATER.

General

Chlorine is added to water in one of three forms: elemental chlorine (chlorine gas), sodium hypochlorite solution or calcium hypochlorite powder, also called high-test hypochlorite (HTH). Chlorine gas reacts rapidly with water to form two compounds - hypochlorous acid (HOCl) and hydrochloric acid (HCl) as follows (reference 5):

Equation 1. $Cl_2 + H_2O \leftrightarrow HOCl + HCl$ $K = 3.9 \times 10^4$ at 25˚C

The forward hydrolosis reaction is virtually complete at pH greater than 4 and chlorine solutions up to 100 mg/L (dilute solutions), as expected with the magnitude of the equilibrium constant (K) (reference 6). Hypochlorous acid, the active chlorine form in disinfection reactions, is a weak acid that further dissociates into two components, the hydrogen ion (H^+) and the hypochlorite ion (OCl^-), as follows (reference 5):

Equation 2. $HOCl \leftrightarrow H^+ + OCl^-$ $K_a = 3.5 \times 10^{-8}$ at 25˚C

$pK_a = 7.5$

As shown in Figure 1, both HOCL and OCl^- species are present to some extent at pH values between 6.5 to 8.5 (reference 3), with equal distribution at pH 7.5 (reference 6). The dissociated hypochlorite ion (OCl^-) predominates at higher pH values, while the undissociated hypochlorous acid (HOCl) predominates at lower pH values. Hypochlorous acid is more reactive than the hypochlorite ion, and a much stronger disinfectant (reference 2). Thus, a lower water pH promotes more efficient disinfection. In general, a water pH of less than 8 is recommended for chlorine disinfection (reference 6). Chlorine will react with many naturally occurring organic compounds in water to produce undesirable disinfectant by-products (DBPs), which may have adverse effects generally associated with long-term exposure (reference 5). Two groups of DBP compounds, trihalomethanes (THMs) and haloacetic acids (HAAs), are currently regulated by the EPA.

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Chlorine Demand

As a strong oxidant, chlorine will combine with many other substances, including ferrous iron, manganese, ammonia and other inorganic and organic material, in water (reference 7). In aqueous solutions with pH 7.0 to 8.5, HOCl reacts rapidly with ammonia to form inorganic chloramines (termed combined chlorine) in a series of competing reactions (reference 5). These reactions are instantaneous, with no appreciable disinfection occurring until this initial "chlorine demand" is met. Subsequent addition of chlorine will results in establishment of a free available chlorine [(FAC), which includes HOCl and OCl^-] residual. Figure 2 shows the "breakpoint chlorination" curve, which is unique for each water source. Thus, the chlorine dosage should be adequate to satisfy the chlorine demand of the source water, but not excessive beyond the breakpoint, as taste and odor problems may occur.

Figure 1. Distribution of Hypochlorous Acid/Hypochlorite versus pH

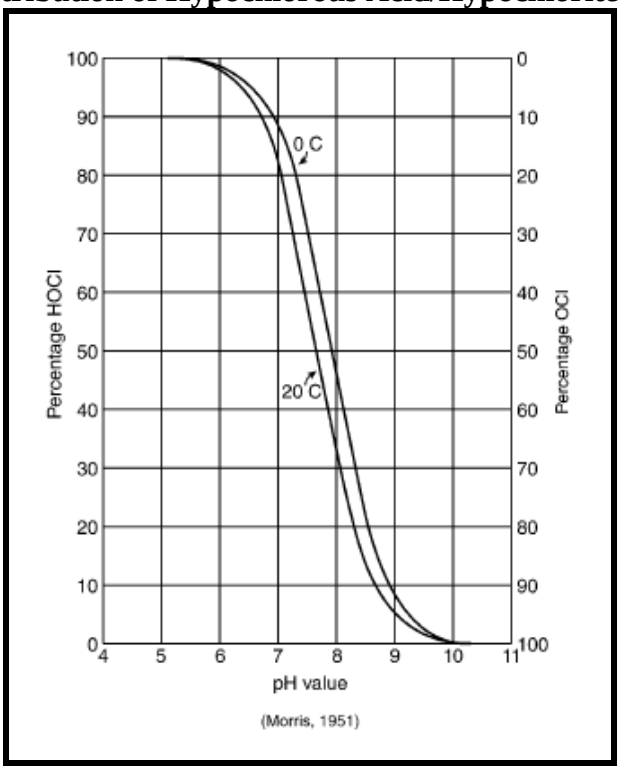
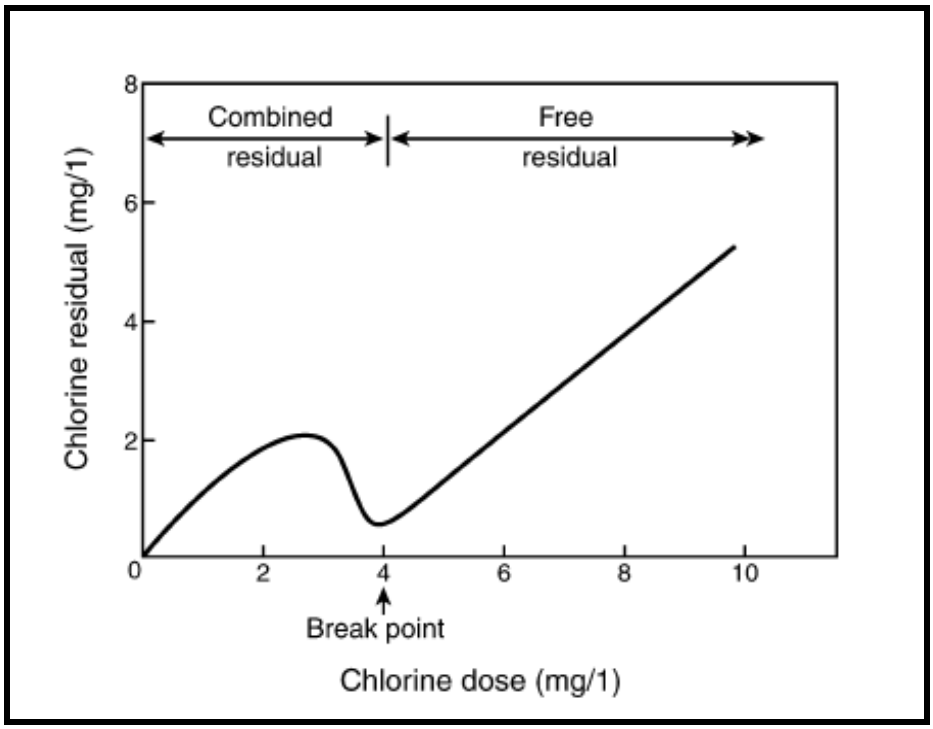


Figure 2. Breakpoint Chlorination Curve



IWPD Forms

General

Chlorine is available in various forms, including calcium hypochlorite (solid), sodium hypochlorite (solution) and as pure chlorine gas. For hand-held IWPDs, chlorine takes the form of either calcium hypochlorite tablets or sodium hypochlorite (including household bleaches). Calcium hypochlorite (chlorinated lime, tropical bleach, bleaching powder, 'HTH') is a powder containing between 30 and 70% available chlorine. It must be stored carefully to prevent deterioration, and although it can cause burns, is generally safe to handle and transport (reference 8). Sodium hypochlorite solutions contain about 1 to 18% chlorine and are thus mostly water. Sodium hypochlorite solution must be stored carefully to prevent deterioration and can cause burns (reference 8).

Chlorine Stabilizers

Ultraviolet rays in sunlight degrade free chlorine compounds in water and significantly decrease disinfection efficacy over time. Chlorine concentrations may be reduced by one-half when exposed to sunlight for only 1 hour (reference 9). To mitigate these

effects, chlorinated derivatives of cyanuric acid, termed isocyanurates, are used to prolong the lifetime of free chlorine in water that is exposed to sunlight. The isocyanurate compound, originally introduced for swimming pool chlorine sanitation in 1960, dissociates in water to form both cyanuric acid, which "stabilizes" free chlorine compounds, and hypochlorous acid, the active disinfectant (reference 9). Chlorine concentrations may be prolonged 3 to 10 times longer in water when cyanuric acid is present in sufficient quantities (reference 9). Studies have shown that cyanuric acid does not interfere with disinfection conditions (reference 10) at concentrations used in drinking water. Some chlorine-using IWPDs may use isocyanurates to prolong chlorine residual in the treated water.

DISINFECTION CAPABILITIES.

General

Chlorine is effective at inactivating bacteria and viruses, and under certain circumstances, *Giardia* (reference 5). However, chlorine has little impact on *Cryptosporidium* oocysts at typical water treatment concentrations (up to 5 mg/L) (reference 5). Chlorine's general disinfection capability with respect to microorganisms can be illustrated in the following way from most effective to least effective:

bacteria > viruses > *Giardia* cysts > *Cryptosporidium* oocysts

The rate of disinfection, or destruction, of microorganisms in water is generally described by the Chick-Watson law (Equation 3, references 11 and 12), which is the basis for the CT values widely used today to determine disinfectant germicidal efficiency. The CT factor is defined as the product of the residual disinfectant concentration (C, in mg/L) and the contact time (T, in minutes) that the residual disinfectant is in contact with the water.

Equation 3. $$\ln \frac{N}{N_0} = -\alpha C^n t$$

Where: N = number of microorganisms at time t
N_0 = initial number of microorganisms
α = inactivation constant
C = disinfectant concentration, moles/L
n = constant of dilution, usually close to 1.0
t = time, min

Chlorine's disinfection capability decreases with decreasing temperature and increasing pH. The EPA has published extensive CT tables for virus and *Giardia* inactivation, for different temperature, pH, and chlorine residual conditions (reference 13). Turbidity can

also have negative effects on chlorine disinfection because particles can shield microorganisms from chlorine. Turbidity particles also typically increase organic content, resulting in higher source water chlorine demand (reference 6).

Environmental Effects on Disinfection Capability

Effect of pH on Disinfection Capability

Since the germicidal efficiency of HOCl is much higher than that of OCl^-, as pH increases, the CT requirement for a given log-reduction increases. Most research has confirmed that chlorine is more biocidal at low, rather than high pH, and the pH effect is more profound for chlorine than other disinfectants, such as chlorine dioxide, ozone, and even combined chlorine (chloramines) (reference 5). Virus inactivation studies have shown that 50% more contact time is required at pH 7.0 than at pH 6.0 to achieve comparable inactivation, and that raising the pH from 7.0 to 9.0 requires a six-fold increase in contact time for comparable viral inactivation (references 5 and 14). However, some viruses have been shown to be more sensitive to chlorine at high, rather than low, pH (references 5 and 15). In these cases, the increased disinfection efficiency may be due to OCl^- forming neutral ion pairs with sodium, potassium, and lithium.

Effect of Temperature on Disinfection Capability

Temperature, over the range appropriate for drinking water, affects the rate of disinfection reactions according to the Arrhenius equation, with colder water slowing inactivation rates. For chlorine, and all other disinfectants, pathogen inactivation effectiveness increases as water temperature rises (reference 5). Additionally, for a given CT value, a low C and a high T is more effective than the reverse (i.e., a high C and a low T), underscoring the importance of temperature in disinfection efficacy (reference 5). Virus studies showed that the contact time must be increased by two to three times when the temperature is lowered by 10˚ C to achieve similar inactivation levels (reference 16).

Effect of Turbidity on Disinfection Capability

Particles responsible for turbidity can surround and shield pathogenic microorganisms from free chlorine, thus decreasing inactivation efficiency. One study investigated indigenous coliform bacteria associated with particulate matter and the protective effects that the particles may have in shielding disinfection. Using sieve and nylon screens to separate particle fractions, coliform bacteria associated with the < 7-µm fraction were inactivated more rapidly than the > 7-µm fraction when exposed to 0.5 mg/L free chlorine at pH 7.0 and 5˚ C (reference 17). The results showed the significance that particle agglomeration and clumping may have on chemical oxidation efficiency. Another study suggested that turbidity impacts on free chlorine disinfection efficiency are

magnified at lower temperatures (reference 18). Free chlorine will rapidly oxidize organic matter associated with turbidity; reducing disinfection efficiency since a free chlorine residual will only appear after all organic matter is oxidized. Thus, higher chlorine dosages may be necessary when using IWPDs to overcome organic matter oxidation and still provide disinfection when treating raw, unfiltered water supplies.

Bactericidal Efficiency

Chlorine is an extremely effective disinfectant for inactivating bacteria under normal conditions. A chlorine inactivation study of pathogenic *Escherichia coli* O157:H7E and wild-type *E. Coli* strains was conducted by the EPA (reference 19). The study showed that at a typical water treatment dosage of 1.1 mg/L FAC, pH 7.0, and 5˚ C, both pathogenic and wild-type *E. coli* strains were inactivated by over 4½ orders of magnitude within 2 minutes (reference 19). The findings indicated that these bacteria were sensitive to chlorine. Certain spore-forming bacteria, such as *Bacillus* or *Clostridium*, may show higher resistance to free chlorine when disseminated as spores (reference 20). Early research in the 1940s involving *E. Coli*, *Pseudomonas aeruginosa*, *Salmonella typhi*, and *Shigella dysenteriae* showed that HOCl is more effective than OCl^- for inactivation of these bacteria (reference 21). Further research showed HOCl to be 70 to 80 times more effective than OCl^- for inactivating bacteria (references 5, 22). Highly turbid water may require higher CT (i.e., longer contact time and/or higher dose) to assure adequate bacteriological disinfection.

Virucidal Efficiency

Chlorine has been shown to be a highly effective viricide. One of the most comprehensive virus studies was conducted in 1971 using treated Potomac estuary water (references 5, 23). The tests were performed to determine the resistance of 20 different enteric viruses to free chlorine under constant conditions of 0.5 mg/L free chlorine residual, pH 7.8, and a temperature of 2° C. The study showed the least resistant virus to be reovirus, requiring only 2.7 minutes to achieve 99.99% inactivation (4-log removal). The most resistant virus was a poliovirus, requiring more than 60 minutes for 4-log removal. The CT range required for 4-log removal was 1.4 to 30 mg·min/L, indicating that adequate disinfection should occur with typical chlorine doses of up to 5 mg/L, depending on the chlorine demand of the source water (reference 23). Other viral survival studies were conducted in the 1970's on 20 cultures, including both laboratory and field poliovirus strains (references 5, 24) under constant conditions of 0.4 mg/L free chlorine residual, pH 7.0, and a temperature of 5˚ C. Test results showed that only two poliovirus strains required 10 minutes to achieve 4-log inactivation (CT = 4 mg·min/L), six poliovirus strains required 100 minutes to reached 4-log inactivation (CT = 40 mg·min/L), and 12 polioviruses strains required 1,000 minutes to reach 4-log inactivation (CT = 400 mg·min/L). Thus, higher FAC levels (> 0.4 mg/L) may be needed

for shorter contact times to ensure 4-log viral inactivation. The SWTR provides the CT values for 4-log inactivation at various source water temperatures with a typical source water pH range of 6-9 (reference 13). Because of chlorine's high efficiency in viral inactivation, CT values are typically governed by *Giardia* (protozoan) CT criteria. Highly turbid water may require higher CT (i.e., longer contact time and/or higher dose) to assure adequate viral disinfection.

Table 1. USEPA SWTR Required CT Values for 4-Log Inactivation of Viruses By Free Chlorine for pH 6-9

Temperature (deg C)					
0.5	**5**	**10**	**15**	**20**	**25**
12	8	6	4	3	2

Cysticidal Efficiency

Giardia cysts

Chlorine has been shown to have limited success inactivating protozoa. Protozoan cysts such as *Entamoeba histolytica* and *Giardia lamblia* are highly resistant to chlorine disinfection and may require prolonged contact times at high chlorine residuals (2-3 mg/l) to achieve 99.9% (3-log) inactivation (reference 20). Past studies have shown that, at 2.5 mg/L free chlorine at 5˚ C and pH 6, a contact time of 30 minutes was needed to achieve a 2-log reduction; 60 minutes was needed when the pH was increased to 7 (reference 25). Comparative studies have shown the resistance of *Giardia* cysts to chlorine inactivation to be two orders of magnitude higher than that of enteroviruses and more than 3 orders of magnitude higher than enteric bacteria (references 5, 26). Extensive CT requirements for *Giardia* cyst inactivation when using free chlorine have been determined for various pH and temperature conditions (reference 13), and are included in Appendix B. A mathematical model for 99.9% (3-log) *Giardia* inactivation was also developed based infectivity data (reference 27):

Equation 4. $$CT = 0.75 (0.9847\ C^{0.1758}\ pH^{2.7519}\ temp^{-0.1467})$$

where:
C = the disinfectant residual concentration
temp = the reaction temperature in degrees Celsius

Equation 4 should generally be used under the conditions it was derived: C between

0.44 and 4.23 mg/L; pH between 6 and 8; and temperature between 0.5 and 5˚ C. However, the CT result would be conservative (more protective) for lower pH values and higher temperatures. The CT result from Equation 4 may be adjusted for higher temperatures by assuming that for each 10˚C increase in temperature, the CT decreases by 0.5 (reference 27).

Cryptosporidium Oocysts

Chlorine is not effective for the inactivation of *Cryptosporidium* oocysts at typical water treatment doses (e.g., 5 mg/L). One *Cryptosporidium* study reported that 80 mg/l of free chlorine required 90 minutes to achieve only a 1-log (90%) inactivation of oocysts, and further indicated that conventional disinfection practices would do little to inactivate waterborne *Cryptosporidium* (references 28, 20). Another study showed a 40% (0.2-log) inactivation of *Cryptosporidium* at CT values of both 30 and 3,600 mg·min/L (references 29 and 5). A 1996 study showed no significant *Cryptosporidium* inactivation with free chlorine concentrations ranging from 5 to 80 mg/L at pH 8, a temperature of 22° C, and contact times of 48 to 245 minutes (references 30, 5). The study also reported that, at pH 6.0 and temperature of 22° C, a 1-log *Cryptosporidium* inactivation required a CT of between 3,000 and 4,000 mg·min/L, and a 3-log *Cryptosporidium* inactivation required exposure to 80 mg/L of free chlorine for 120 minutes (references 30 and 5). Therefore, IWPDs using only chlorine disinfection for treatment (i.e., without filtration) should not be relied upon for protection from *Cryptosporidium* contamination. The EPA has not adopted CT tables for *Cryptosporidium* in the proposed Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), choosing instead to concentrate on tighter source protection and more effective *Cryptosporidium* disinfectants, such as chlorine dioxide and ozone (reference 31).

CHLORINE TOXICITY

When added to water, chlorine reacts with natural organic matter in water to form disinfection by-products. Ingestion of chlorine and its halogenated by-products, including THMs and HAAs, can result in adverse health effects when consumed in large enough quantities for long periods of time. The EPA regulates chlorine, total trihalomethane (TTHMs) and (the sum of) five HAAs (HAA5) in drinking water systems that use chlorine for disinfection. The EPA established a maximum residual disinfectant level (MRDL) of 4.0 mg/L for chlorine and maximum contaminant levels (MCLs) of 0.80 and 0.60 mg/L for TTHM and HAA5 compounds, respectively (reference 32). Potential health effects from ingestion of water containing free chlorine above 4.0 mg/L include eye, nose and throat irritation, stomach discomfort, nausea and vomiting. Evidence from animal and human studies suggests that chlorine and hypochlorite solutions themselves probably do not contribute to the development of cancer or any toxic effects (reference 33). Potential health effects from ingestion of water with elevated

levels of TTHMs over a long period of time include liver, kidney or central nervous system problems, as well as the increased risk of cancer. Some studies also show an association between high levels of TTHMs and an increased risk of early term miscarriage (references 31 and 33). Potential health effects from ingestion of water with elevated levels of HAA5 compounds over a long period of time include the increased risk of cancer (reference 31). Generally, short-term exposure to elevated levels of THMs and HAAs for healthy adults does not result in adverse health effects (reference 34). For IWPD use, the risk of illness and death resulting from exposure to pathogens in drinking water is very much greater than the risks from chlorine and its DBPs (reference 34). However, manufacturer recommended chlorine dosages should be followed to minimize the potential for DBP formation and exposure. Toxicity studies of cyanuric acid, the stabilizing compound in isocyanurates, have shown no carcinogenic, mutagenic or teratogenic effects, even at levels considerably above those typically found in drinking water (reference 35).

CONCLUSIONS

Chlorine as an IWPD is effective at inactivating bacteria and viruses, and under certain circumstances, *Giardia*. However, chlorine has little impact on *Cryptosporidium* oocysts at typical water treatment concentrations. Individual Water Purification Devices using only chlorine disinfection for treatment (i.e., without filtration) should not be relied upon for protection from *Cryptosporidium* contamination. Colder temperatures, higher pHs, and higher turbidities all tend to have an adverse effect on disinfection capability. Generally, short-term exposure to chlorine DBPs at IWPD manufacturer-recommended chlorine dosages of up to 5 mg/L should not result in adverse health effects. To avoid potential adverse health effects, longer contact times should be used in place of higher chlorine dosages, provided sufficient free available chlorine remains after oxidizing organic matter. Some chlorine-using IWPDs may use isocyanurates to prolong chlorine residual in the treated water. Toxicity studies involving isocyanurate compounds have not shown any adverse human health effects at typical drinking water concentrations. Table 2 provides a summary of the disinfection capabilities of chlorine.

Table 2. Chlorine Disinfection Capabilities

Parameter	Chlorine Disinfection
General Disinfection Capability	Cysts most resistant. Achieving cyst inactivation will ensure adequate bacteria and virus inactivation. Disinfection capability generally follows: Bacteria > Viruses > *Giardia* > *Cryptosporidium*
Bacteria	Effective at reasonable CT values for IWPD use.
Viruses	Effective at reasonable CT values for IWPD use. Use EPA SWTR CT table for recommended CT values (Table 1).
Giardia Cysts	Effective at reasonable CT values for IWPD use. Use EPA SWTR CT tables for recommended CT values (Appendix B).
Cryptosporidium Oocysts	Ineffective, even at high CT values. Not practical for IWPD use.
Effect of Temperature	Colder water temperatures require higher CT values. Use a two-fold increase in CT for every 10˚C decrease. Use longer contact time instead of higher dosages to achieve higher CT values.
Effect of pH	Disinfection efficiency increases with decreasing pH. Recommend pH less than 8.0 to ensure presence of hypochlorous acid (HOCl)
Effect of Turbidity	Higher turbidity generally reduces disinfection capability. Higher dosages may be necessary to ensure the presence of free chlorine after oxidation of organic matter.
Health Effects	Chlorine, THMs and HAAs have potential health concerns at elevated levels. IWPD manufacturer-recommended dosages are not likely to cause adverse health effects for healthy adults.

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APPENDIX A
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APPENDIX B
CT VALUES FOR INACTIVATION OF
***GIARDIA* CYSTS BY FREE CHLORINE**

Table B-1. EPA SWTR Required CT Values for 3-Log Inactivation of *Giardia* By Free Chlorine at 0.5 degrees Celsius of Lower

pH	Chlorine Concentration (mg/L)													
	≤ 0.4	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.8**	**2**	**2.2**	**2.4**	**2.6**	**2.8**	**3**
≤ 6	137	141	145	148	152	155	157	162	165	169	172	175	178	181
6.5	163	168	172	176	180	184	189	193	197	201	205	209	213	217
7.0	195	200	205	210	215	221	226	231	236	242	247	252	257	261
7.5	237	239	246	253	259	266	273	279	286	297	298	304	310	316
8.0	277	286	295	304	313	321	329	338	346	353	361	368	375	382
8.5	329	342	354	365	376	387	397	407	417	426	435	444	452	460
≤ 9.0	390	407	422	437	451	464	477	489	500	511	522	533	543	552

Table B-2. EPA SWTR Required CT Values for 3-Log Inactivation of *Giardia* By Free Chlorine at 5 degrees Celsius

pH	Chlorine Concentration (mg/L)													
	≤ 0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3
≤ 6	97	100	103	105	107	109	111	114	116	118	120	122	124	126
6.5	117	120	122	125	127	130	132	135	138	140	143	146	148	151
7.0	139	143	146	149	152	155	158	162	165	169	172	175	178	182
7.5	166	171	175	179	183	187	192	196	200	204	209	213	217	221
8.0	198	204	210	216	221	227	232	238	243	248	253	258	263	268
8.5	236	244	252	260	267	274	281	287	294	300	306	312	318	324
≤ 9.0	279	291	301	312	320	329	337	345	353	361	368	375	382	389

Table B-3. EPA SWTR Required CT Values for 3-Log Inactivation of *Giardia* By Free Chlorine at 10 degrees Celsius

pH	Chlorine Concentration (mg/L)													
	≤ 0.4	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.8**	**2**	**2.2**	**2.4**	**2.6**	**2.8**	**3**
≤ 6	73	75	78	79	80	82	83	86	87	89	90	92	93	95
6.5	88	90	92	94	95	98	99	101	104	105	107	110	111	113
7.0	104	107	110	112	114	116	119	122	124	127	129	131	134	137
7.5	125	128	131	134	137	140	144	147	150	153	157	160	163	166
8.0	149	153	158	162	166	170	174	179	182	186	190	194	197	201
8.5	177	183	189	195	200	206	211	215	221	225	230	234	239	243
≤ 9.0	209	218	226	234	240	247	253	259	265	271	276	281	287	292

Table B-4. EPA SWTR Required CT Values for 3-Log Inactivation of *Giardia* By Free Chlorine at 15 degrees Celsius

pH	Chlorine Concentration (mg/L)													
	≤ 0.4	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.8**	**2**	**2.2**	**2.4**	**2.6**	**2.8**	**3**
≤ 6	49	50	52	53	54	55	56	57	58	59	60	61	62	63
6.5	59	60	61	63	64	65	66	68	69	70	72	73	74	76
7.0	70	72	73	75	76	78	79	81	83	85	86	88	89	91
7.5	83	86	88	90	92	94	96	98	100	102	105	107	109	111
8.0	99	102	105	108	111	114	116	119	122	124	127	129	132	134
8.5	118	122	126	130	134	137	141	144	147	150	153	156	159	162
≤ 9.0	140	146	151	156	160	165	169	173	177	181	184	188	191	195

Table B-5. EPA SWTR Required CT Values for 3-Log Inactivation of *Giardia* By Free Chlorine at 20 degrees Celsius

pH	Chlorine Concentration (mg/L)													
	≤ 0.4	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.8**	**2**	**2.2**	**2.4**	**2.6**	**2.8**	**3**
≤ 6	36	38	39	39	40	41	42	43	44	44	45	46	47	47
6.5	44	45	46	47	48	49	50	51	52	53	54	55	56	57
7.0	52	54	55	56	57	58	59	61	62	63	65	66	67	68
7.5	62	64	66	67	69	70	72	74	75	77	78	80	81	83
8.0	74	77	79	81	83	85	87	89	91	93	95	97	99	101
8.5	89	92	95	98	100	103	105	108	110	113	115	117	119	122
≤ 9.0	105	109	113	117	120	123	126	129	132	135	138	141	143	146

Table B-6. EPA SWTR Required CT Values for 3-Log Inactivation of *Giardia* By Free Chlorine at 25 degrees Celsius

pH	Chlorine Concentration (mg/L)													
	≤ 0.4	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.8**	**2**	**2.2**	**2.4**	**2.6**	**2.8**	**3**
≤ 6	24	25	26	26	27	27	28	29	29	30	30	31	31	32
6.5	29	30	31	31	32	33	33	34	35	35	36	37	37	38
7.0	35	36	37	37	38	39	40	41	41	42	43	44	45	46
7.5	42	43	44	45	46	47	48	49	50	51	52	53	54	55
8.0	50	51	53	54	55	57	58	60	61	62	63	65	66	67
8.5	59	61	63	65	67	69	70	72	74	75	77	78	80	81
9.0	70	73	75	78	80	82	84	86	88	90	92	94	96	97